ARE WE MAINTAINING THE PRODUCTIVITY OF FOREST LANDS? ESTABLISHING GUIDELINES THROUGH A NETWORK OF LONG-TERM STUDIES

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ABSTRACT

Protecting the inherent capacity of forest land to grow vegetation is a goal of modern forest management and a legal requirement of the Forest Service, U.S. Department of Agriculture. Options for judging this capacity include potential tree growth and potential net primary productivity of all vegetation. Evidence exists that this capacity is degraded by substantive losses of site organic matter and soil porosity. If such potentials were known for each site, and if changes in key soil properties were calibrated against these potentials, the relative impacts of forest practices could be assessed objectively and directly. Unfortunately, few data have been collected for establishing such calibrations, and managers must turn to soil-quality monitoring standards that are based more on professional judgment than on rigorous science. This paper describes a cooperative study between Research and Administrative arms of the Forest Service to establish such calibrations through a national network of long-term productivity studies.

INTRODUCTION

Sustaining the long-term productivity of our Nation's forests is an ethical and economic aim of forest management. Ethics relates to a willingness to sacrifice personal gain for the good of a social pyramid with society at its apex and the land at the base (Leopold 1949). Economics refers to protecting the land's ability to meet consumer demands by sustaining a profitable flow of forest products. For the Forest Service, U.S. Department of Agriculture, there is a legal reason, too. Among the World's nations, the United States is unique in its mandate for good stewardship of public lands. By law, the Forest Service must monitor the effects of management practices to ensure sustained productivity.

This paper serves several purposes. First, it reviews the main concepts of forest site productivity. It also acquaints the reader with the legal basis for protecting long-term productivity and its implications for field monitoring. Next, the paper summarizes what is known about productivity decline due to poor management. Finally, it describes a newly established Forest Service cooperative program that tackles the subject head-on.

SITE PRODUCTIVITY CONCEPTS

The productivity of a forested site is shaped by abiotic factors of climate, soil, relief, and mechanical damage by fire, flood, or wind. Productivity also is shaped by biotic factors involving tree genetics, stand age, stocking and degree of competition, and stand health as conditioned by insects, diseases, other pests, and symbionts. Except for such random disturbances as fire, flood, or wind, abiotic factors change relatively slowly under natural conditions. In contrast, most of the biotic factors (tree age, stocking, health) are dynamic. For example, growth rates vary with age. Usually, they are low during juvenility, accelerate with approaching maturity, and decline thereafter. Some abiotic and many biotic factors can be affected by management—either by design, or inadvertently. And the degree to which this is understood depends on one's definition of "productivity."

Timber Site Quality—Historically, the forestry concept of site productivity has centered on the capacity of the land for growing wood of commercial value. Traditionally, this capacity or "timber site quality" is expressed as volume increment averaged over a period of years. Timber site quality has both an actual and a potential component.

Actual and potential volume increment rarely coincide. The former is the fraction of a site's capability that is actually realized by management. Generally, this is less than the site's potential. For example, trees spaced widely in understocked stands will have lower collective growth rates than trees growing closely. Furthermore, trees weakened through severe and prolonged competition or from mechanical injury are susceptible to insects and diseases, which decreases absolute growth. All of this means that the actual site productivity of a given unit of forest land varies continually. A corollary is that management can affect apparent productivity simply by manipulating stocking, species, and pests.

Besides its actual productivity, each land unit has a theoretical maximum productivity, or an upper limit for

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the rate of wood growth when the stand is fully stocked and other factors are held constant. This is the concept of absolute or potential site quality (Spurr 1952), only part of which generally is realized by management. Estimating this potential is difficult. Variable density yield functions may be manipulated to approximate the potential upper limit of wood growth, but empirical yield tables generally reflect norms for stocking and incorporate incipient degrees of stress from insects and diseases. Thus, yield tables would tend to underestimate potential site quality.

Although it is the historical measure of site quality, wood production has a relatively low priority in the tree's allocation of photosynthate. Production of roots, foliage, and reproductive structures all take precedence (Grier and others 1989). Thus, wood production is a rather incomplete and limited measure of the quality of the whole site for forest growth. Is there an alternative?

Total Site Productivity—The fundamental ecological measure of site productivity is total dry matter produced by autotrophic plants. This "net primary productivity" (NPP) is expressed by the equation:

$$NPP = GPP - Rs_A$$

where GPP is gross primary productivity from total photosynthesis and Rs_A is respiration of all parts of autotrophic plants.

Units of NPP generally are expressed as dry mass of organic matter produced per unit area each year, such as Mg/ha/yr. Not all NPP appears as standing biomass. Some that is produced annually is cycled to the forest floor and soil or is consumed by grazing animals. The quantity that does accumulate can be defined as:

$$NPP_B = NPP - NPP_C - NPP_D$$

where NPP_B is the net primary productivity accumulated annually in standing biomass of all plants above ground, below ground, or both; NPP_C is the biomass consumed annually by pathogens, insects, and grazing animals; and NPP_D is the actual production of detritus from litterfall and root mortality.

As indicated by the paucity of estimates of NPP available for forests of western North America (table 1), NPP and its individual components are not estimated easily. Tables and equations for estimating tree stem volumes from diameter and height are common, but these generally have a commercial bias (bole volumes to a minimum top diameter, rather than dry matter) and do not account for branches, foliage, or roots. Usually, destructive sampling, drying, and weighing are used to relate the mass of individual tree components through regression to more easily measured tree dimensions. Measurements taken at different times can then be used to estimate standing NPP. Obviously, such work is extremely costly, and the equations often are specific only to the stand in question. The detritus component (NPP_D) can be estimated by weighings of periodic litterfall, but this can be complicated by storm-induced detritus. Estimating NPP_C is even more difficult and often is ignored, although it can be a sizable component of NPP. Insects and diseases can reduce productivity by as much as 25 to 50 percent in western forests (Stewart 1985; Stoszek 1973).

Table 1—Estimates of biomass and NPP for some western conifer forests. From Grier and others (1989). NPP includes above ground (A) and below ground (B)

Dominant tree species	Location	Age	Component	Biomass	NPP
		Years		*Mg/ha*	*Mg/ha/yr*
Abies amabilis mix	Washington	23	A	52	6.1
amabilis mix	Washington	23	A	77	17.9
amabilis mix	Washington	180	A	446	4.5
amabilis mix	Washington	180	A	583	16.7
lasiocarpa mix	Arizona	106	AB	357	8.6
Pinus ponderosa	Arizona	150	AB	162-250	4.9-5.7
monticola	Idaho	103	A	415-675	11.4-17.6
monticola	Idaho	103	A	488-794	13.1-20
monticola mix	Idaho	100-250	A	265-330	4.7-10
Pseudotsuga menziesii	Washington	22	AB	139	10.8
menziesii	Washington	36	A	172	13.8
menziesii	Washington	36	A	203	17.5
menziesii	Washington	40	A	249	9.9
menziesii	Washington	40	A	306	15.4
menziesii	Washington	73	AB	307	5.7
menziesii	Oregon	90-110	AB	661	12.7
menziesii	Oregon	150	AB	865	10.5
menziesii	Oregon	450	A	560	2.1
Tsuga heterophylla	Oregon	26	A	193	32.2
heterophylla	Oregon	26	A	231	37.7
heterophylla	Oregon	121	A	1,062	22.8

Climatic conditions favoring plant growth favor NPP. Thus, it is not surprising to see that the highest average rates of NPP occur in warm temperate and tropical forests, and the lowest are found in cold or arid regions (table 2). Lieth (1975), in analyzing NPP rates reported for all forest biomes, suggested that a productivity ceiling exists at a little over 30 Mg/ha/yr under the most favorable conditions of precipitation and temperature. Interestingly, dense young forests of *Tsuga heterophylla* (Raf.) Sarg. can achieve this level of NPP (table 1). Much, perhaps three-quarters of a site's total NPP, is directed below ground (Grier and others 1981), where a very high proportion soon becomes detritus from senescing fine roots and mycorrhizae. On the average, only 10 to 30 percent of total tree biomass is maintained below ground, but as much as three-quarters of ecosystem organic carbon is stored there and in the forest floor (table 2).

Just as with timber site quality, NPP has both an actual and potential component that varies with the same factors shaping wood production. Actual NPP increases steadily as a stand develops, and reaches a maximum rate with the advent of canopy closure, when the site has achieved its carrying capacity for foliage (Grier and others 1989). At this point, leaf mass stabilizes barring disturbance, and litterfall may represent a fairly constant proportion of stand NPP. Potential NPP depends then on stand age. However, at any given stage of forest development, potential NPP would be the total amount of dry mass produced per year when the site is fully stocked with vegetation. Grier and others (1989) provide an extensive discussion of problems and approaches in estimating above- and below-ground biomass and NPP. As we shall see, site productivity concepts have a direct bearing on how public forest lands are managed in the United States.

PUBLIC LAND LAW AND MONITORING REQUIREMENTS

The Multiple Use-Sustained Yield Act of 1960 (Sec. 4.[b]) binds the Forest Service to achieve and sustain outputs of various renewable resources without permanently impairing the productivity of the land (USDA Forest Service 1983). This mandate was reinforced in the National Environmental Policy Act of 1969 and the Forest and Rangeland Renewable Resources Planning Act of 1974. Directions were refined further by Sec. 6.(g)(3)(c) of the National Forest Management Act of 1976 (NFMA) which charges the Secretary of Agriculture with ensuring research and monitoring of the effects of each management system to protect the permanent productivity of the land (USDA Forest Service 1983).

In response to NFMA, an independent Committee of Scientists was appointed by the Secretary of Agriculture to help develop regulations for implementing the law. This led to a Code of Federal Regulations for Forest Planning which, among other stipulations, requires the Forest Service to monitor the effects of prescriptions, including "significant changes in land productivity" (Code of Federal Regulations 1985). The Chief of the Forest Service then directed each of the nine Forest Service administrative Regions to develop monitoring procedures for detecting significant changes in land productivity over a planning horizon (a rotation).

IMPLEMENTING THE REGULATIONS

The Forest Service's first task was to define the scope of its monitoring responsibility. "Land productivity" might encompass wildlife, watershed, fisheries, esthetic, and timber values. All of these are valid components of productivity, but they are not equally measurable. Some are intangible, subjective, or temporally unstable. Discussions with the Office of General Counsel and other parties helped form a more objective and usable definition of "land productivity" and "significant change" (USDA Forest Service 1987).

"Land productivity" was defined as a soil's capacity to support plant growth as reflected by some index of biomass accumulation. Although it may not be the broadest measure of productivity, plant growth is a useful index of ecosystem health. Losing a soil's plant growth capacity also means losing the site's capacity for sustaining other resource values. Further, a "significant change" in productivity was defined as the minimum level of reduced plant growth that is detectable using current technology.

Thus, the Forest Service is charged with protecting the inherent capacity of the soil to sustain plant growth, and to monitor the consequences of forest practices to the end that this capacity is not endangered. What, then, is "the inherent potential of the soil?" Assessing significant changes under operational field conditions is not simple, nor has

Table 2—Characteristics of organic carbon in vegetation above and below ground, the forest floor (FF), and mineral soil to a depth of 1 m in some major forest biomes. Modified from Powers and Van Cleve (1991), as compiled from several sources

Forest biome	Carbon above ground				Carbon below ground			Total in ecosystem	Prop. in FF + b.g.
	NPP	Veg.	FF	Total	Veg.	Soil	Total		
	Mg/ha/yr	Mg/ha							Pct
Semiboreal	2.4	76	29	105	24	159	183	288	74
Cool temperate	4.8	148	22	170	32	132	164	334	56
Warm temperate	10.6	84	10	94	20	96	116	210	60
Semiarid temperate	5.7	55	12	67	7	86	93	160	66
Subtropical	6.7	120	6	126	16	101	117	243	51
Tropical	10.1	157	4	161	15	107	122	283	44

the soil's potential been quantified. If current productivity is too variable, and if potential productivity is not easily assessed, could a substitute measure be used?

The Forest Service believes it is the soil. Along with climate, relief, and biology, soil sets the limits on productivity within a region through its control of nutrient, moisture, and air supplies to tree roots. "Soil productivity" is the term that describes this. If we knew the potential productivity inherent to each soil type, and the important factors that distinguish one soil from another, then the changes in those factors caused by management could be used to indicate changes in inherent, potential productivity. Thus, soil becomes a logical focus for monitoring. The Forest Service's Watershed and Air Management Staff has assumed responsibility for monitoring soil productivity. Monitoring strategy is based on three principles:

1. Management practices create soil disturbances.
2. Soil disturbances affect soil and site processes.
3. Soil and site processes control site productivity.

Monitoring soil and site processes directly is not feasible. Instead, monitoring focuses on measurable soil variables that reflect important site processes. For example:

Site process	Soil-quality monitoring variables
Soil erosion	Percentage soil cover or surface disturbance, soil bulk density, amount of soil loss, sediment production, presence of soil rills or pedestals, etc.
Water availability	Potential infiltration, saturated hydraulic conductivity, soil bulk density, puddling, plant moisture stress, soil water-holding capacity, etc.
Nutrient availability	Percentage soil cover, soil color and organic matter content, soil loss or displacement, etc.
Gas exchange	Soil bulk density or permeability, puddling, presence of mottles, water logging, etc.
Root growth and uptake	Soil structure, strength, or bulk density, water table depth, etc.

Soil scientists in each National Forest Region, with the approval of the Regional Forester, are directed to identify soil-quality monitoring variables judged to be important for their Region, to prepare Regional soil-quality standards, and to devise suitable methods for monitoring soil disturbances (USDA Forest Service 1987). This is aimed at ensuring the protection of soil productivity in the pursuit of land management objectives.

SOIL-QUALITY MONITORING STANDARDS

The principle behind the Forest Service approach is illustrated in figure 1A. For any given soil and site, a change in a key soil variable (for example, a loss in porosity) will lead ultimately to a change in potential productivity. If the soil variable is not closely linked with productivity, changes in the condition of that variable will have little or no bearing on productivity (potential productivity remains stable along the "line of no change" in fig. 1A). Obviously, a key feature is that the soil monitoring variable must have a close link with potential productivity.

The conceptual model in figure 1A is simplistic. It implies that potential productivity—the "dependent variable"—is a stable and known value. In reality, there is a belt of uncertainty surrounding a productivity estimate that is due to climatic vagaries and to limits in our knowledge. This uncertainty is shown as a shaded band about the line of no change in figure 1B. Uncertainty about the true value of potential productivity leads to uncertainty about how much change a soil can undergo before productivity is affected. Recognizing this, and based largely on collective judgment, the Forest Service estimates that a

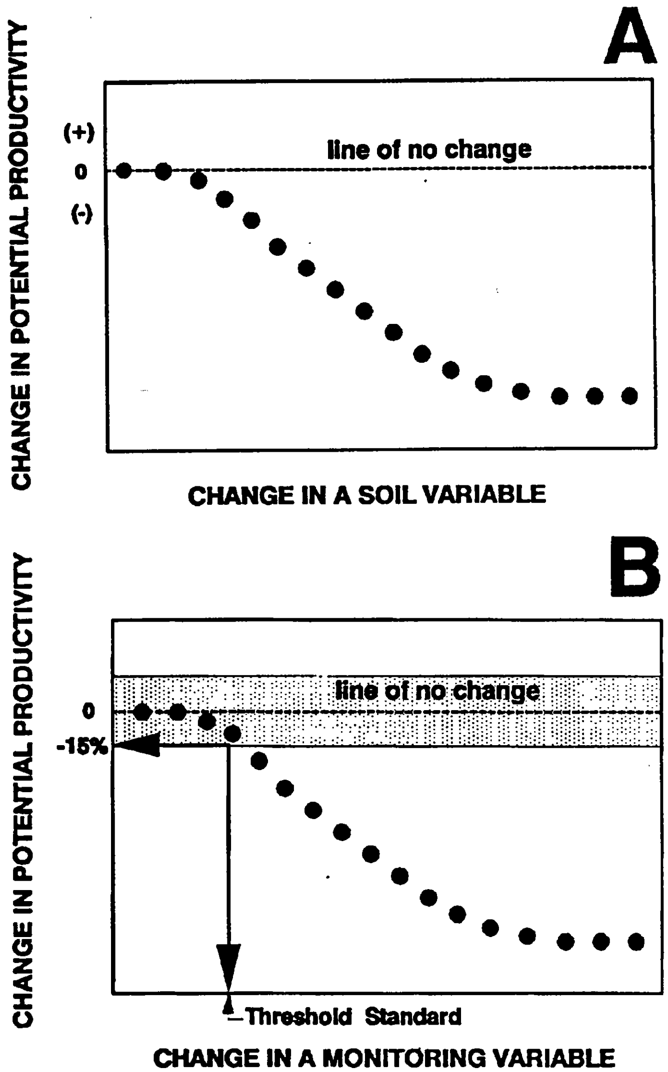

Figure 1—Hypothetical relationship between potential productivity and a key soil variable. A, as properties of a soil variable change, productivity declines from its potential before disturbance; B, in practice, a belt of uncertainty exists about the estimate of potential productivity for an undisturbed site. Threshold soil-quality monitoring standards are set at the level of soil change corresponding to a statistically detectable (15 percent) decline in potential productivity.

true productivity decline would need to be as great as 15 percent to be detectable by modern monitoring methods. Thus, soil-quality threshold standards are being set to detect a decline in potential productivity of at least 15 percent (fig. 1B). This does not mean that the Forest Service tolerates productivity declines of up to 15 percent, but merely that it recognizes problems with detection limits.

Soil-quality monitoring is seen as a three-stage process (USDA Forest Service 1987):

1. Implementation monitoring to ensure prescribed soil management practices are implemented as designed (a National Forest System [NFS] responsibility).
2. Effectiveness monitoring to determine the effectiveness of prescribed soil management practices (a NFS responsibility).
3. Validation monitoring to determine whether monitoring standards and guidelines are appropriate to maintain soil productivity (a Research responsibility).

What is the technical basis for soil-quality monitoring standards? Often, they are based on the collective judgment of professionals because the subject has not been tackled from a direct, scientifically rigorous perspective. But is there sound evidence that soil property changes are associated with substantial declines in productivity?

HAS PRODUCTIVITY DECLINED?

Effects of massive slope failure and loss of the soil mantle on long-term productivity are so obvious that they need not be documented here. But do less dramatic activities also degrade? Evidence from the United States tends to be confounded, or short term and inconclusive (Powers and others 1990). The best clues come mainly from abroad where forestry has been practiced longer, records are more complete, or multiple short rotations have occurred. World findings have been reviewed recently by Powers and others (1990), and the main points are summarized here.

Removal of Biomass

Utilization standards affect rates of biomass and nutrient removal, and nutritional aspects have drawn most of the research attention. Generally, one-tenth of total ecosystem nitrogen and a smaller fraction of ecosystem phosphorus is contained in the biomass of young, mature forests (table 3). Of this, at least half of the nitrogen and phosphorus is contained in foliage and branches. As a rule, a 1 percent increase in biomass removal means a 3 percent increase in nutrient removal (Switzer and others 1981). Direct evidence of productivity decline from biomass removal is rare. Sterba (1988), in a thinning study in Austria, found that residual trees had 12 percent greater growth if felled trees remained on the site than if they had been removed. However, the reason for this remains speculative.

Organic matter and nutrient losses in conventional timber harvests and rotations seem unlikely to affect potential productivity on most sites (Wells and Jorgensen 1979). However, shorter rotations deplete nutrients much more rapidly than do long rotations. Switzer and others (1981) estimated that with whole-tree harvesting (the removal of all aboveground biomass), three 20-year rotations in loblolly pine would remove three-quarters more organic matter and twice the nitrogen as one 60-year rotation. Even so, this amounted to less than 10 percent of the nitrogen in the ecosystem. To date, assessments of the impacts of increased utilization or shortened rotations are based mainly on model projections and not empirical evidence. They are predicated on many assumptions lacking rigorous proof.

Loss of Organic Matter

In South Australia, Keeves (1966) showed that radiata pine planted on sandy soils grew much more poorly in the second rotation than in the first. Squire and others (1985) demonstrated that the decline was triggered by the burning of logging slash, which led to nutrient and moisture stress. The effect was evident by the time of crown closure. They showed that the growth of second rotations could exceed that of first rotations if logging residues were retained. Findings suggest that organic matter retention is particularly important on infertile, droughty sites.

Organic matter in the forest floor (surface residues of plants and animals that are not yet soil) has singular significance in respect to productivity. Although its mass is only a small fraction of that in the standing forest (table 2), its nutrient content often equals or exceeds the combined total for the trees and understory vegetation (table 3). Substantial losses of forest floor material have degraded some sites. Litter raking—the regular removal of freshly

Table 3—Ranges in total nitrogen (N) and phosphorus (P) contents reported for ecosystem components of young, mature true fir, pine, and Douglas-fir forests in North America. Modified from Kimmins and others (1985)

Ecosystem component	True fir		Pine		Douglas-fir	
	N	P	N	P	N	P
	kg/ha					
Trees						
Above ground	80 - 686	12 - 83	180 - 556	12 - 31	84 - 728	18 - 112
Below ground	24 - 72	4 - 12	12 - 117	2 - 21	30 - 90	5 - 18
Understory	2 - 50	[1]t - 14	1 - 54	t - 5	5 - 66	1 - 9
Forest floor	666 - 2,300	9 - 103	80 - 1,240	9 - 103	110 - 1,249	19 - 115
Soil to 1-m	5,237 - 14,000	3,212 - 6,317	1,753 - 5,554	146 - 4,457	1,170 - 15,400	3,878 - 3,900

[1]t = trace.

fallen conifer needles—was practiced in central European conifer forests for centuries to obtain bedding straw for farm animals. Wiedemann (1935) found that several decades of litter raking in Scots pine plantations on sandy soils in eastern Germany led to higher soil densities and to growth declines of nearly two site classes. Soils also were lower in fertility (Baule and Fricker 1970). Similar results were found for radiata pine in New Zealand, where 26 years of litter raking led to appreciable declines in soil nutrients, an increase in bulk density, and about a 12 percent decline in growth (Dyck and Skinner 1990).

Loss of Soil Porosity

Sands (1983), working with radiata pine in Australia, found sizable increases in soil density on sites converted from pasture to pine plantations. The effect increased by the second rotation because of multiple passes of machinery, and approached a growth-limiting density at depth. In the United States, Froehlich and others (1986) and Helms and others (1986) reported that trees growing on compacted soils contained only about one-fifth the volume of trees growing on less compacted soils nearby. Growth losses depend on the degree of compaction. The greater the proportional increase in soil density, the greater the productivity loss (Froehlich and McNabb 1984).

Freezing and thawing promotes natural recovery. But for coarse-textured soils on warmer sites, effects largely are irreversible (Sands 1983). And on finer textured soils, natural recovery may take decades (Hatchell and others 1970). Sands (1983) concluded that desirable soil physical properties depended largely on the maintenance of soil organic matter. In time, soils will compact of their own weight without further disturbance if organic matter is lost appreciably from the profile (Sands 1983).

Loss of Topsoil

Although soils often contain vast amounts of nutrients (table 3), relatively small losses of surface soil can affect productivity. This is because many nutrients, such as nitrogen, are concentrated in organic matter. Organic matter, in turn, is not distributed evenly throughout the soil, but is concentrated near the surface and decreases rapidly with depth (Powers 1989). In New Zealand's pumice region, displacing logging debris and a thin layer of topsoil into windrows during site preparation produced nutrient deficiencies and led to a 30 percent loss in volume growth by mid rotation (Dyck and Beets 1987). Similar results were reported in the United States for loblolly pine in North Carolina (Fox and others 1989), for ponderosa pine in California (Powers and others 1988), and for Douglas-fir in the Pacific Northwest (Minore 1986). Tew and others (1986), examining practices in the Piedmont region of the southeastern United States, estimated that piling logging residues into windrows removed two to three times more nitrogen and phosphorus than whole-tree harvesting.

Topsoil also is lost through erosion if surface organic matter is removed appreciably or if surface soils are compacted. Removing the forest floor exposes a soil to rainfall, particle displacement, and sealing of surface pores. Depending on slope steepness, this can lead to erosion rates 40 to 1,200 percent greater than those caused simply by logging (Megahan 1987). Compaction or topsoil displacement exposes a soil surface with a lessened capacity to absorb rainfall, and leads to greater runoff and erosion. Although erosion following timber harvest and site preparation can be equivalent to rates reported for agriculture (Neary and others 1984), the period of accelerated loss tends to be brief as the site revegetates. Effects of surface erosion on long-term productivity are not well known and can only be inferred.

Summarizing the Evidence

Substantive losses of surface organic matter and soil porosity have led to documented declines in productivity. Organic matter and porosity influence productivity through their link with more fundamental processes, as indicated by the conceptual model in figure 2. But beyond conceptual models, we lack a specific understanding of what a given change in porosity or organic matter means in terms of its long-term effect on productivity. As Miller and Hazard (1987) have said, uncertainty and skepticism will persist until we establish and maintain studies that help us document and understand the long-term effects of forest practices on productivity.

Although soil-quality monitoring standards now in use tend to focus on changes in porosity and organic matter, they are based mainly on "best professional judgment" from extrapolation of anecdotal studies or from general observations that are subject to various kinds of bias. Definitive calibrations such as depicted in figure 1 simply do not exist. Because of this, many standards may face legal challenge as to whether they are too restrictive, or not restrictive enough. The effectiveness of current standards must be validated. If standards are found wanting, they must be improved.

Work is needed at both the fundamental and applied level to quantify the effects of soil disturbance on potential productivity—not only in a timber management sense, but in a more fundamental sense as well. We know little about the inherent carrying capacity of forest sites for producing vegetation, or about its relationship to key soil variables. Yet, this relationship must be known if we hope to produce accurate calibrations (fig. 1A) and effective soil-quality monitoring standards (fig. 1B). Such calibrations must be developed if the Forest Service is to meet its legal and ethical responsibility. Clearly, Foresc Service Research has the mandate for conducting such work. But the scope and scale of the problem are far too vast for Forest Service Research to tackle alone. There must be a partnership.

A COOPERATIVE NATIONAL STUDY

In December 1986, at the annual meeting of the Soil Science Society of America in New Orleans, an informal session was held for Forest Service attendees. There, P. E. Avers—National Soils Group Leader from the Washington Office—outlined the problem of soil-quality monitoring facing NFS, and asked for assistance from Research. Further discussions were held between Avers, D. H. Alban, and R. F. Powers. The following June, Avers and four scientists from the North Central, Pacific Northwest, Pacific

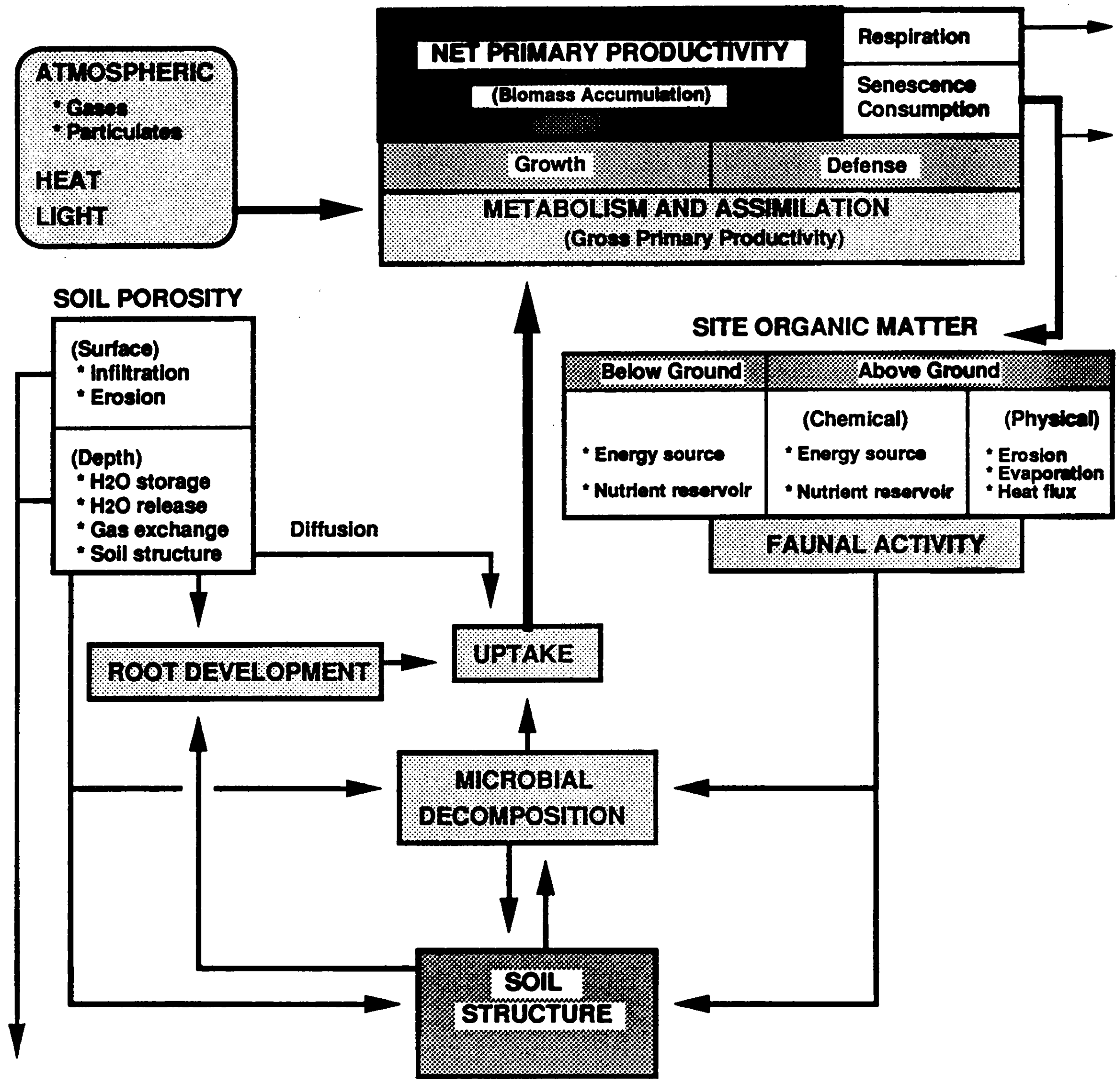

Figure 2—Conceptual model of the roles of soil porosity and site organic matter in regulating the processes controlling site productivity.

Southwest, and Southern Forest Experiment Stations met in a California field setting to review the scope of the problem and discuss possible solutions. This was followed by a March 1988 session in St. Louis to plan a formal strategy for Research and NFS collaboration. Attendance was expanded to include a scientist from the Southeastern Station and one representative each from Timber Management, Timber (now Forest) Management Research, and Forest Environment Research staffs of the Washington Office.

These meetings led to the creation of two major documents. The first was an extensive, critical literature review concerning the long-term impacts of forest practices on potential productivity. Part of this was a proposal for a new national research effort. The paper was presented before an international gathering of scientists in July 1988, and was published in the peer-reviewed proceedings of the conference (Powers and others 1990). The second document was a plan prepared in October 1988 by Research and NFS personnel outlining a cooperative national Forest Service study of the impacts of management practices on long-term soil productivity (LTSP). The plan was presented to the Chief's staff and received extensive technical review both in the United States and abroad. In 1989 it was approved by the Washington Office (Powers and others 1989), and the plan now serves as a template for more detailed regional studies.

Objectives

Cooperation is under way between Forest Service Research and the National Forest System with the objectives of (1) quantifying the effects of soil disturbance from management activities on soil productivity with the aim of establishing site-specific calibrations such as are hypothesized in figure 1B; (2) validating standards and techniques for soil-quality monitoring; and (3) understanding the fundamental relationships between soil properties, long-term productivity, and forest management practices (Powers and others 1989). These objectives can be stated as complementary "Research" and "Development" topics.

Research	**Development**
How does soil disturbance affect:	*Facilitate soil monitoring efforts by:*
• Carbon allocation.	• Calibrating changes in soil properties against (i) stand productivity; and and (ii) total productivity.
• Water use.	• Evaluating/developing practicable field monitoring methods.
• Nutrient use.	• Developing means for extending results to a broad array of sites.
• Other processes.	
• Resistance to pests.	
• Fundamental productivity.	

A fundamental purpose of the study is to develop understanding of the joint role of soil porosity and site organic matter in their effect on site processes controlling productivity. An applied purpose will be to validate soil-quality standards and monitoring methods used by NFS, and to develop new procedures as needed. Highlights described later are condensed from Powers and others (1989).

Coordination

Three levels of coordination are described to ensure the achievement of national and regional objectives in the national LTSP program.

National Oversight—National coordination and review for LTSP is provided by Forest Management Research, Forest Environment Research, Timber Management, and Watershed and Air Management Washington Office staffs. Coordinating activities include:

1. Developing priorities and funding opportunities.
2. Reviewing Station/Region implementation plans.
3. Highlighting accomplishments.

National Technical and Regional Steering Committees are responsible for establishing and conducting the LTSP studies.

National Technical Committee—The National Technical Committee for LTSP consists of Principal Investigators and Regional Soil Scientists who presently are, or who expect to be, involved in implementing and maintaining studies and interpreting study results. This committee, chaired by a Principal Investigator appointed by the National Oversight Committee, will have five main responsibilities:

1. Reviewing study proposals to ensure that scientific methods are consistent and appropriate to meet program objectives.
2. Establishing a national data base of research results.
3. Informing the Washington Office of progress, needs, opportunities, and substantive findings.
4. Coordinating and preparing results for publication.
5. Reviewing, evaluating, and incorporating modifications to the proposals.

Regional Steering Committee—The Regional LTSP Steering Committee consisting of the Experiment Station Principal Investigator, Regional Soil Scientist, and Regional Silviculturist initiates and encourages cooperative and collaborative ties with National Forests, Ranger Districts, and other researchers. This committee identifies individual study sites, prepares specific study plans based on this general plan, and implements the studies. The Regional Committee shares responsibility with National Forests and Ranger Districts for ensuring public awareness of the program. Departures from procedures described in the study plan must be approved by both the National Technical Committee and the National Oversight Committee. Study sites should be identified in the Monitoring Plan for each National Forest.

Affiliations—Prospective collaborators from a dozen U.S. universities have formed an ad hoc committee to explore ways to secure funding for joint LTSP research with Forest Service scientists. International collaboration also is under way through British Columbia's Ministry of Forests and New Zealand's Forest Research Institute for parallel LTSP studies using our protocol.

Experimental Protocol

Treatments—A broad range of manipulations of soil porosity and site organic matter are applied on benchmark soils within the major commercial forest types of the United States. Work began in 1989 in the Pacific Southwest and Southern Regions on lands expected to be managed intensively in the decades ahead. In 1990 and 1991 the LTSP program expanded to the Northern and Eastern Regions (fig. 3), and it continues to expand both domestically and abroad.

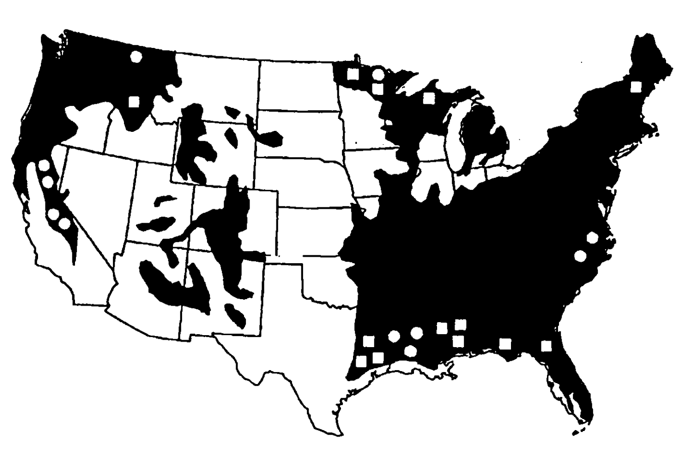

Figure 3—The commercial forest region of the conterminous United States showing national LTSP installations. Circles: sites installed or undergoing installation. Squares: sites proposed for installation in 1992. Some symbols represent more than one installation.

Within each Region and forest type, and across a broad range of productivity classes, about a dozen timbered sites will be selected for treatment. Sites will be characterized before treatment according to a standard protocol (Powers and others 1989). A core series of organic matter removal and soil compaction treatments will be assigned randomly to 0.4-ha treatment plots. All possible combinations of the following main effects will produce nine core treatments to be applied at each site.

Main effect		Treatment level
Organic matter removal	OM0	Boles removed, only
	OM1	Boles and crowns removed (whole-tree harvesting)
	OM2	Boles, crowns, understory, and forest floor removed (all aboveground biomass)
Soil compaction	C0	No compaction
	C1	Intermediate compaction (halfway between C0 and C2)
	C2	Compaction to about 80 percent of the difference between hypothetical growth-limiting bulk density (Daddow and Warrington 1983) and bulk density existing before treatment at 10-20 cm.

This cluster of nine treatment plots will cover the range of site organic matter and soil porosity changes apt to occur under present or future forest management. Other treatments—such as topsoil removal, conventional harvest and site preparation techniques, or ameliorative practices—may be installed at the prerogative of the Regional Steering Committee, provided that they do not confound or alter the core cluster of nine treatments. Work has begun on about a dozen U.S. sites as of this writing, and another dozen should be on line by 1992 (fig. 3).

Generally, each 0.4-ha treatment plot will be planted with seedlings of the appropriate timber type and a mixture of the best available genetic stock. Natural regeneration (seeding or sprouting) may be substituted where appropriate. The aim is to favor superior growth without narrowing genetic diversity. Each treatment plot will be split in half, creating two 0.2-ha subplots of about 340 trees each (fig. 4), with a measurement plot established from the fourth row of trees inward in each subplot. After establishment, one subplot will be kept weed free. In the other, regional vegetation will be encouraged to grow with the trees—the aim being to promote complete vegetative recovery as rapidly as site conditions permit so that the site approaches full carrying capacity for vegetative growth. This split-plot arrangement creates a means for side-by-side comparisons of (1) stand productivity vs. total vegetative productivity, and (2) the effect of competing vegetation on tree growth.

Measurements—Soil properties capable of being monitored operationally will be measured periodically and correlated with vegetative growth. Because all treatment plots

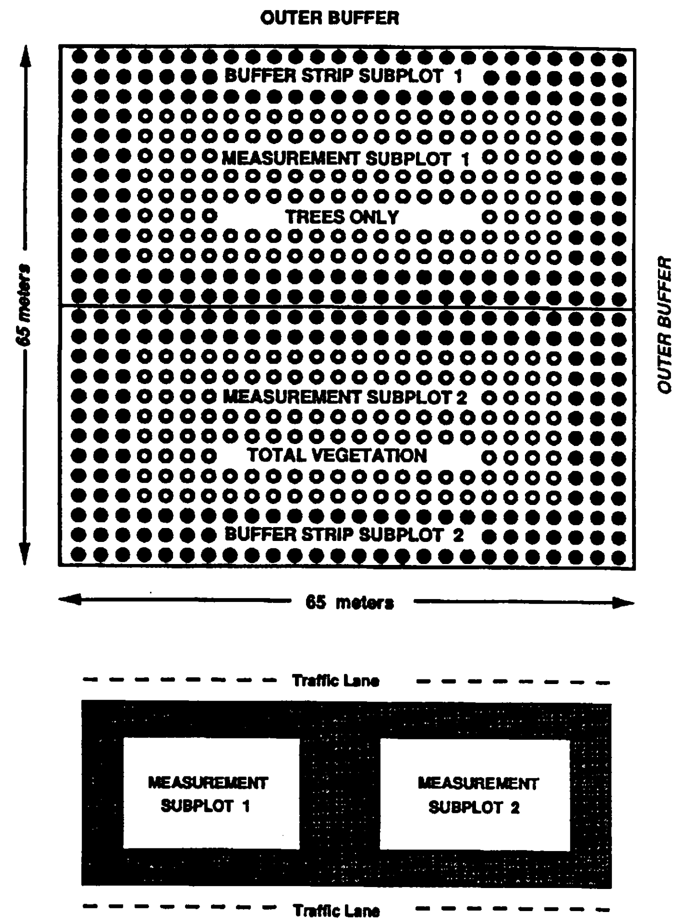

Figure 4—Possible layouts for 0.4-ha treatment plots and 0.2-ha subplots. Tree locations are indicated by circles. Each measurement subplot contains three rows of buffer trees (dark circles) along its outer border. The square plot (upper) would be appropriate for full-suspension aerial harvesting systems. The rectangular plot (lower) is possible where materials can be removed by a loader positioned in a traffic lane just outside the plot.

are adjacent in an installation, comparative rates of vegetative growth will provide a precise measure of differences in site productivity. Wood and total tree biomass production in "trees only" subplots provide the basis for traditional "timber site quality" measures as affected by soil disturbance, with "OM0,C0" treatments providing a baseline control. Also, the "total vegetation" subplots provide a more comprehensive measure of "total site productivity" as reflected in total NPP. Productivity measured near the point of crown closure will provide a precise estimate of maximum potential productivity. And throughout the study, comparing each treatment against the OM0,C0 control will be an excellent means for judging whether soil changes have affected the potential productivity of the land. Measurements are:

Pre- and posttreatment measurements dealing with—		Postplanting measurements dealing with—
Organic matter	Porosity	Productivity
Mass by component	Bulk density	Stocking
• Logging slash	Soil strength	Height
• Forest floor	Infiltration	Diameter
• Mineral soil	Moisture release	Damage
Nutrients by component	Saturated hydraulic conductivity	Aboveground biomass in:
• Logging slash	Erosion	• Trees (by component)
• Forest floor	Soil temperature	• Other vegetation (by component)
• Mineral soil		Carbon partitioning
Decomposition and mineralization		Species diversity

A standard weather station and datalogger will be installed at each site to monitor air and soil temperature, wind speed and direction, relative humidity, total and photosynthetically active solar radiation, precipitation, and evapotranspiration. Stations will be compatible with others installed throughout the country, and will add to our monitoring base for detecting climatic change and its possible impact on the productivity of the land.

Responsibilities and Implementation

Costs, estimated at about $74,000 per installation for the first 5 years, will be shared by NFS and Research. In general, NFS is responsible for establishing and maintaining the sites. Research is responsible for data collection, analysis, and publication. Study plans prepared jointly by Stations and Regions will detail the responsibilities. Contacts and field visits with research and practicing entomologists, pathologists, and wildlife specialists should be frequent. Once funded, approximately 14 months will be the minimum time needed to locate and install a series of study sites within a timber type (fig. 5). The first strong indication of long-term treatment effects can be expected in 5 to 10 years after planting on average sites.

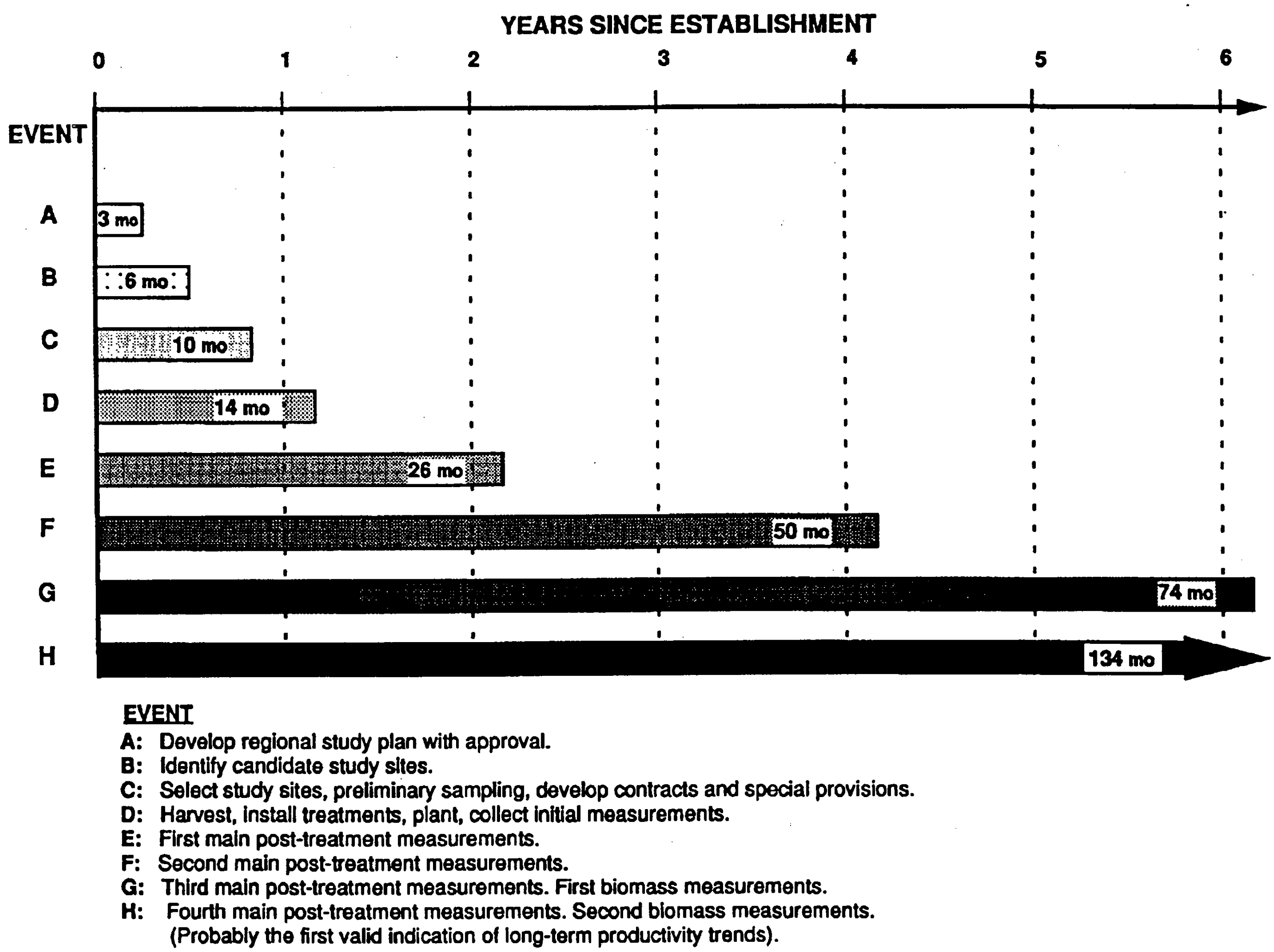

Figure 5—Sequence and timeline for locating, installing, and measuring study plots. Trees would be thinned according to best management practices and the stand characteristics of that treatment. Sampling would continue throughout the rotation.

SUMMARY

Our ability to maintain a site's productive capacity faces increasing challenge through public review of Forest Land Management Plans and timber sales. In response to NFMA, Forest Service Regions are developing threshold soil-quality standards for detecting declines in potential soil productivity. Such standards are based on best available information. Often, this amounts to professional judgment, because research has not addressed the problem squarely. Professional judgments will be subject to repeated challenge from many sectors. Results from this cooperative study will provide credible responses to many of these challenges, and will address related research needs across the Nation. An immediate benefit is a clear show of good faith by the Forest Service to adhere to the spirit of NFMA and to tackle the problem aggressively.

This national network of study sites will provide the scientific basis for validating soil-quality standards established by NFS, and creates a research opportunity of unusual scope and significance. Initially, existing standards for monitoring soil quality will be compared with interim findings and can be adjusted to reflect the most recent research results. With time, more substantive results will be available for future planning. All Regions and Stations are encouraged to participate to ensure the success of this joint program.

The experimental design provides researchers with the framework for comparing stand production with more fundamental measures of productivity. Because a gamut of stress conditions is imposed deliberately on vegetation, pest and disease interactions are likely, and multidisciplinary collaboration will be encouraged. Basic models of soil and growth processes can be integrated with site and climatic data to extrapolate findings to a broad array of sites, and to project the possible impacts of changing climate on future productivity. The work fosters close cooperation between Research and NFS, and opens doors for important work with university and industry colleagues.

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